PHOTON-STOP R&D PROPOSAL

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As part of Fermilab's Very Large Hadron Collider (VLHC) feasibility study, a photon-stop is being explored as a possibility to intercept the intense synchrotron radiation in the VLHC – stage 2 at room temperature. The photon-stop, if feasible, promises significant savings in cooling power compared to a solution in which the synchrotron radiation is extracted from a beam screen at cryogenic temperatures. The photon-stop is a device, which protrudes into the beam tube at the end of each bending magnet to absorb the synchrotron light emitted by the beam in the second magnet upstream from it.

The following proposes a multi-step R&D plan towards the realization of such a device. In a first step a photon stop prototype would be submitted to a thermal test in the Advanced Photon Source photon-beam. In a second step the cryogenic engineering concept would be verified in a liquid nitrogen environment. Finally, a full blown vacuum test series of the photon-stop in a VLHC like setting in the Advanced Photon Source beam-line is proposed. The proposal contains as well a rudimentary lay-out of a measurement of the photon-stop impedance.

1) INTRODUCTION

As part of Fermilab's Very Large Hadron Collider (VLHC) feasibility study, a photon-stop has been proposed as a possibility to intercept the intense synchrotron radiation in the VLHC – stage 2 at room temperature[1]. The photon-stop, if feasible, promises significant savings in cooling power compared to a solution in which the synchrotron radiation is extracted from a beam screen at cryogenic temperatures. The photon-stop is a device, which protrudes into the beam tube at the end of each bending magnet to absorb the synchrotron light emitted by the beam in the second magnet upstream from it. A first pass engineering design of such a device has been presented[2]. The results of numerical impedance calculations[3] give additional support to the viability of the approach.

The following proposes a multi-step R&D plan towards the realization of such a device. In a first step a photon stop prototype would be submitted to a thermal test in the Advanced Photon Source (APS) photon-beam. In a second stage, a cryogenic test of the prototype could be performed. A full blown vacuum test series of the photon-stop in a VLHC like setting is proposed as final stage. The following describes briefly the characteristics of the SR in the VLHC2 with its present design (section 2), a brief description of the test-beam-line and the characteristics of the SR beams at the APS (section 3), and the proposals for the different stages of the R&D plan towards the realization of a VLHC photon-stop (sections 4,5&6). Section 7 proposes a possible test of the photon-stop in a proton beam line. Finally, section 8 summarizes all required R&D tasks.

2) SR IN THE VLHC

A brief summary of the characteristics of the SR emitted by the VLHC-2 bending magnets is given in the following. A more detailed study of the exact VLHC-2 SR beam characteristics would exceed the scope of this preliminary R&D proposal. Such a work can be considered as one of the tasks that the photon-stop R&D has to address.

The basic SR parameters of the VLHC-2 in its present form are indicated in Table 1. The formulas used to calculate these parameters are resumed in [1].

SR power per beam per meter p_{SR} (W/m)	4.7
Critical energy (keV)	8.03
# of emitted photons per meter per second ($m^{-1}s^{-1}$)	$1.2 \cdot 10^{16}$

Table 1: Synchrotron radiation parameters in the VLHC2.

Figure 1 shows the spectrum of SR radiation emitted by the VLHC bending magnets, that is the power per 14 m long magnet per beam per photon-energy interval. The low energy spectrum in the plot is not plotted further than to 1 % of the critical energy. At the upper end the spectrum was arbitrarily cut off at 4 E_c. The spectrum shown in Figure 1 accounts for ~95 % of the photon flux.
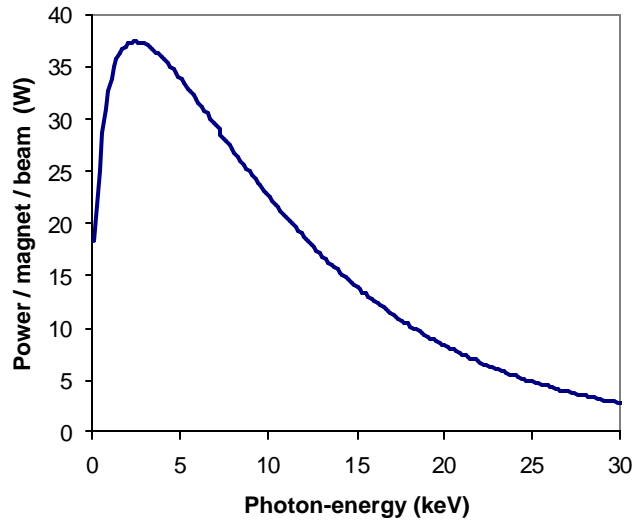
Figure 1: Spectral power distribution of SR photon flux (1 beam) from a 14 m long VLHC2 dipole.

Some preliminary estimations of the photon beam size, as seen by the photon-stop are indicated in the following table:

RMS width (azimuthal) of the strip of SR at the PS (mm)	0.5
RMS width of the strip (radial) of SR at the PS (mm)	10
Incidence angle of SR on photon stop (deg)	~ 90

Table 2: Geometrical properties of the VLHC-2 SR (PS stands for photon-stop).

The SR experiments proposed in the following aim at matching as closely as possible the characteristics of the SR emitted in the VLHC-2 bending magnets. To exactly determine the required collimation scheme for the experiments in the APS beam-line, a detailed study of the SR characteristics (e.g. including the effect of the spectral distribution of the SR flux) is necessary.

3) MEASURING AT THE ADVANCED PHOTON SOURCE

The Advanced Photon Source (APS) at Argonne National Laboratory is a national synchrotron-radiation light source research facility. The APS is funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Figure 2 shows a schematic of the 1.104 km circumference APS with its numerous SR beam-lines.

The synchrotron light is produced by 60 bunches a $3.6 \cdot 10^{10}$ electrons, giving an average 100 mA e⁻-beam, with a particle energy of 7 GeV. There are two distinct sources of SR around the ring:

- 0.84 T peak field undulator magnets, which can be tuned to produce a first harmonic peak in the range 5-25 keV photon energy.
- 0.6 T bending magnets which produce a spectrum of radiation, typically characterized by the critical energy, here 19 keV.

The total SR power emitted per undulator/bending magnet is 4.4/6.83 kW, at a photon flux of $1.3 \cdot 10^{19}$ photons/sec/mrad^2/mm^2 (at 30 m from the source) and $1.6 \cdot 10^{13}$ photons/sec/mrad. The fluxes are given for a 0.1 % band-width. The bending magnet power is given for the total fan width of 78 mrad – actually only 7 mrad are extracted toward the experimental sections.

The accelerator physics group at APS has extensive experience in the design of SR absorbers, commonly used in the APS ring[4]. In particular the APS ring features crotch absorbers, and wedge absorbers, absorbing parts of the SR generated in the bending magnets and undulators. They operate at various levels of absorbed SR power, i.e. 145 W/mm (of fan width) in the case of the crotch absorbers. In addition, the APD/APS maintains special beam-lines that are available for photon-stop testing. Table 3 lists the characteristics of these "diagnostics" beam-lines. The diagnostics-undulator produces a lower photon flux and SR than the regular undulator (see Table 3).

Line	SR power	Characteristic photon energy	Source	Availability
Sector 35 ID	0.83 kW	5 keV-25 keV*	Undulator	Y
Sector 35 BM	0.6 kW	~20 keV	Bending Magnet	Y

Table 3: Characteristics of the APS diagnostics beam-lines (* first harmonic).
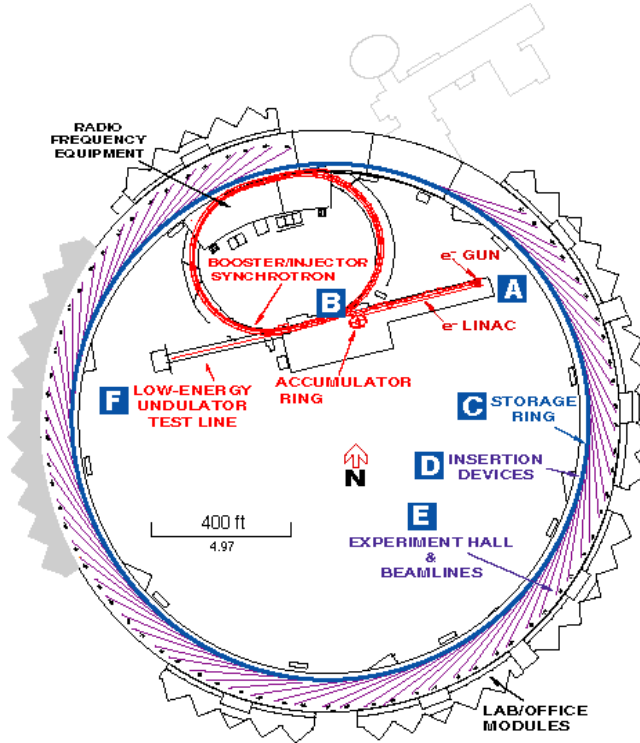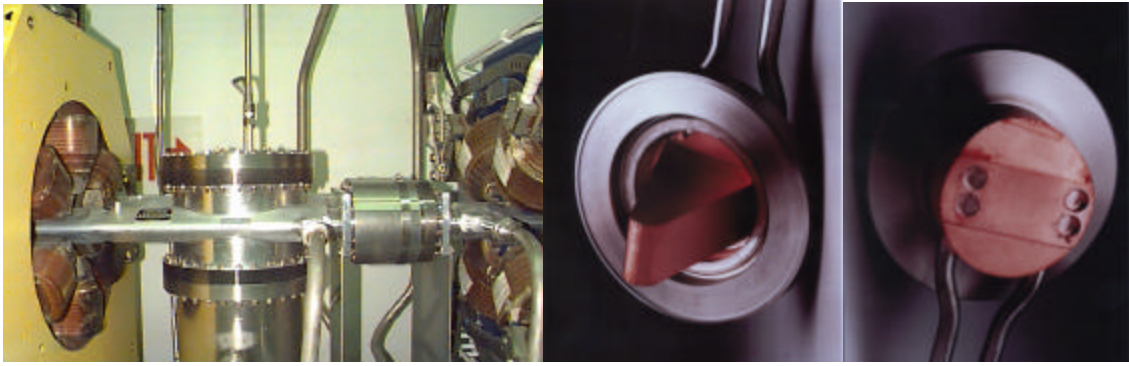

Figure 2: Schematic of the APS ring.

Figure 3: Photographs of a wedge-absorber in the APS. a) View of absorber in the ring (the lower container houses an ion pump), b) front view, c) back view.
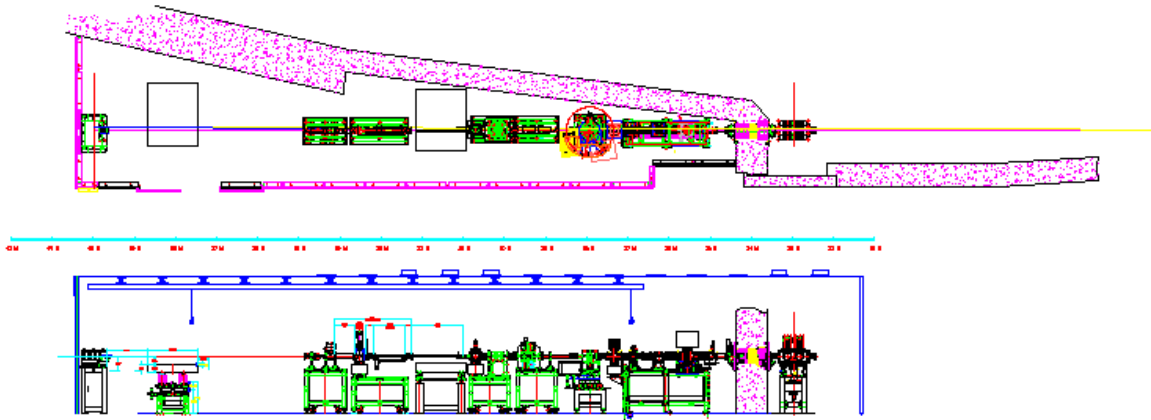

Figure 4: APS diagnostics beam-line layout. The light beam enters from the right.

4) PHOTON-STOP R&D – PHASE 1

The second pass engineering design of the VLHC-2 photon-stop[5], currently underway, will be compatible with the experimental access port ("cross") for photon-stop testing in the APS-APD diagnostics beam-line. For that reason the photon-stop will be shorter (total length ~5 inches) than required in an accelerator magnet setting. A sketch of the cross is shown in Figure 5. The cross consists of a vertical access tube, allowing access from top (photon-stop) and bottom (pump) and the horizontal flanges for the insertion into the SR beam line. In addition there are two more horizontal access ports (at 60 degrees from the beam line), one for an infra-red window for temperature measurement and the second for additional instrumentation (such as for example an RGA).

The phase 1 photon-stop test would consist primarily in performing a thermal test of the VLHC photon-stop insert in the APS photon-beam line using the above described test-cross. In addition, first estimates of the vacuum related issues could be undertaken. For the purpose of the stage-1 tests, only the photon-stop insert, consisting of the cooling tubes, the absorber and the top flange, would be assembled, cleaned and baked. An array of thermo-couples would allow to measure the temperature evolution in the photon-stop during exposure to the synchrotron radiation. The thermo-couples would as well allow a

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calibration of the infra-red sensor which is an integrated part of the SR absorber test set-up. The thermo-couples, infrared sensor, flow-regulators and temperature sensors in the cooling water pipes serve to evaluate the main thermal parameters of the photon-stop, i.e. the absorber surface temperature, coolant temperature, flow-rate, etc. The vacuum part of the measurements could proceed as described in the following: A RF-quadrupole mass analyzer (RGA) – attached to one of the horizontal instrumentation ports - can be used to get a first estimate of the gas desorption rate during exposure to SR. Combined with the tunable sputter ion pump – attached directly below the test-section - an estimate of the pumping speed required to cope with the desorbed gas-load and thus a first validation of the vacuum models can be obtained. In addition, a fatigue test could be performed to estimate the long-term effects of radiation on the absorber piece. The assembly of the photon-stop insert will allow to gain experience in manufacturing and give indications of its cost in a mass-production scheme. The time-scale of such a test, including design of the device, procurement and extensive testing could be several months. The cost of such a test is mostly related to the design, assembly and procurement of the photon-stop prototype. The cost of instrumentation and testing will be comparatively small.

As a useful extension of this experiment we propose to attach some thermo-couples to the vacuum envelope surrounding the photon-stop to obtain a first estimate of the photon scattering rate. If the power deposition in the neighboring region due to scattered photons appears high, similar tests with an improved absorber design could be conducted.
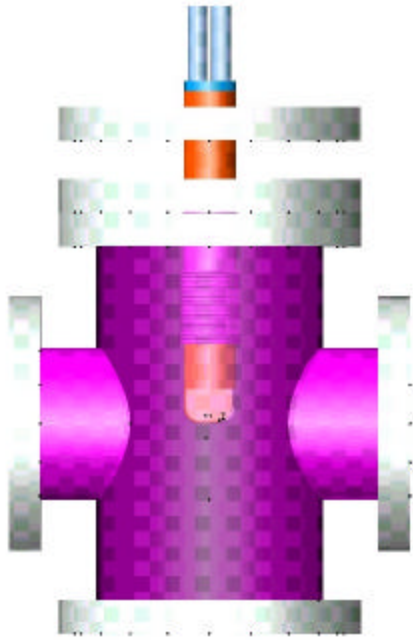

Figure 5: Sketch of photon-stop – eng. design II inserted in the "cross" in the APS diagnostics beam-line.

5) PHOTON-STOP R&D – PHASE 2

In a second stage, the photon-stop prototype could be tested in a cryogenic environment (without photon-beam), using the experimental set-up proposed in Figure 6. This set-up consists of a vacuum vessel which contains a cold bore, cooled by a spiral wrap of tubes containing LN_2 at ~80 K emulating the 100 K beam-screen. The complete photon-stop assembly, (insert, outer hull,..etc) would be mounted into the vacuum vessel in the same way it would attach to the magnet cryostat in the accelerator. The thermal interference between the cold tube and the warm photon-stop could be measured with an array of thermo-couples, mounted on the 300 K insert, the outer photon-stop hull and via a measurement of the LN_2 boil-off rate. The SR heating can be simulated with an electrical heater mounted at the tip of the photon-stop. This experiment would as well address the issue of freezing in the cooling water lines in the absence of SR heating. Different refrigeration fluids could be tested as well as the cooling tube heater system. If the same prototype as in test 1 is to be used the issue of the photon-stop system length becomes relevant. The outer envelope of the photon-stop has to negotiate a temperature drop from ambient to ~ 100 K and absorb the thermal radiation from the ~300 K insert. This is a challenge in a 50 cm long system, and even more so in a short prototype. One could argue, that whatever solution works in the short photon-stop case will work as well for the longer, real case. However, it is at this point not clear if such a short design is cryogenically feasible. An additional advantage of the short prototype is that the components of the stage 2 cryogenic testing (vacuum vessel,..) can be made accordingly smaller and cheaper.
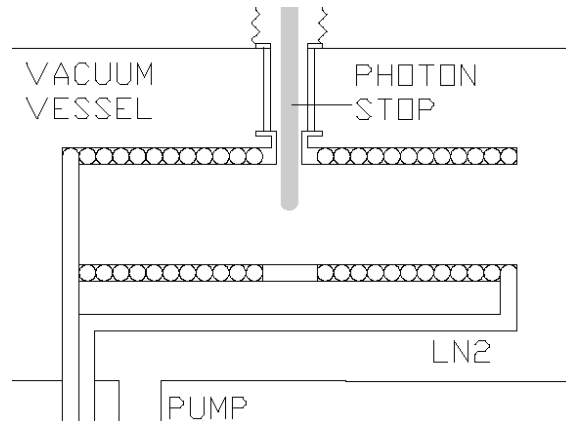

Figure 6: Photon-stop cryogenic test set-up.

6) PHOTON-STOP R&D – PHASE 3

In a final stage the photon-stop insert tested in stages 1&2 would be integrated into a complete VLHC-2 vacuum system assembly. These experiments would serve to simulate the photon-stop in a VLHC-2 setting, i.e. including sections of the regular beam tube arrangement with the perforated liner and the cold-bore cryo-pump. However, given the amplitude of such tests, they would only be justified in the frame of a "real" VLHC

project. Although further analysis of the vacuum process is required to determine exactly the parameters of interest, such a test, similar to the former SSC and LHC experiments[6],[7], would consist in measuring the rate of photo-desorption of weakly bound gas atoms/molecules from the photon-stop – and neighboring surfaces. The new elements in the experiments proposed here, compared to former measurements conducted at the BINP[6],[7], are - 1) a much higher SR flux - 2) a higher critical energy (8 keV vs. 3 keV) and – 3) the concentration of massive photo-desorption to a small area, namely the photon-stop. For a retractable photon-stop device the shared regime (i.e. part of the radiation hitting the photon-stop and part of the radiation hitting the beam-screen wall at grazing incidence) could be tested.

The cold-bore tube – liner configuration should be as similar as possible to the proposal for the VLHC-2[8], that is a 40 mm OD bore tube operating at ~5 K and a ~30 mm ID beam screen tube, with flattened top and bottom operating at ~100 K.

 Figure 7 shows a preliminary schematic of the apparatus for such a test. This apparatus consists of the following elements :

- An SR-filtering section (here ~ 50 cm), with collimators and absorbers to prepare the SR beam to the specified VLHC-2 characteristics.
- A ~1.2 m long, 40 cm diameter vacuum vessel containing the VLHC-2 beam-tube mock-up with the photon-stop and vacuum instrumentation.
- Ion pumps (IP) and mass analyzers (RGA) at the two extremities of the vacuum vessel to provide the beam-tube pumping and the vacuum measurements at the boundaries of the experimental area.
- An end-section consisting of a calorimeter (CM) and the ultimate photon-stop at the end of the experimental line.

At the heart of the experimental apparatus are two ~50 cm long sections of cold-bore – beam-screen assemblies that replicate the VLHC-2 beam tube system. The cold-bore tube in each section is cooled with liquid helium (LHe) supplied with its own (~30 lter) cryostat. An improved design would use only one larger dewar. Not shown in Figure 7 are the gas-return pipes from the cold-bore cryo-vessels to the reservoir. The 4.2 K surfaces are shielded from thermal radiation with a liquid nitrogen (LN_2) shield – in the form of a spiral-wrap tubing around the cold-bore cryo-vessel. The LN_2 shield circuit provides as well the coolant for the beam-screen cooling tubes, thus the test-beam-screen would be operated at ~ 80 K instead of 100 K as currently proposed in the VLHC-2 feasibility study[8]. The inlets and outlets for the beam-screen, cold-bore shield circuit of the two beam-tube sections are not shown in Figure 7. The LN_2 flow-rates, tubing diameter, ..etc have not been determined yet. The dewars, supplying the cryogen to the 5 K cold-bore sections have as well their own LN_2 shields (stagnant LN_2). To facilitate the beam-screen production the beam screen could consist of one piece, extruded from copper, including the cooling channels. In the two 50 cm long sections in which the beam-screen is surrounded by the cold-bore tube, pumping holes are required. In the center, at the photon-stop location a larger hole is required for the passage of the photon-absorber. Three additional holes are required for the pumping/measurement ports. At the extremities of the 50 cm cold-bore sections the cold-bore tube and the beam screen must be welded together to seal the cryo-pump vacuum area, since the cold-bore tube is discontinued over the central photon-stop region. A similar technique was used as well in the BINP experiments.

The (water-cooled) photon-stop protrudes though the beam-screen, using a technique presented in detail in [2,5]. It is attached to the vacuum-vessel envelope and the beam-screen. There are two (or three) room temperature (!) pumping ports with Ion-pumps and RGA's attached in the test-section – one opposite to the photon-stop and another in the middle of the second beam-screen section. The pumping port opposite to the photon-stop will require special attention since it drains desorbed gas from the photon-stop and thus can introduce a large error in the measurement of the pressure in the photon-stop area. The central RGA will allow measurement of the gas-density at the photon-stop location, the RGA in the beam-screen section will allow monitoring the gas-density at sections away from the photon-stop (which can as well be hit by SR in a shared regime).
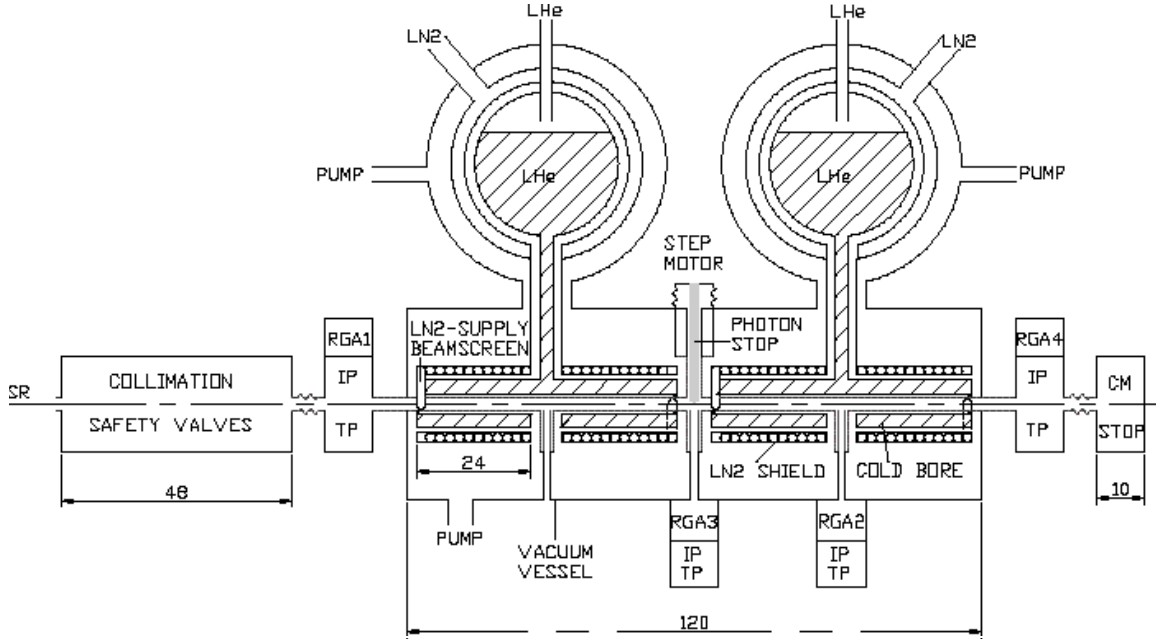

Figure 7: Sketch of possible stage 2 photon stop vacuum test apparatus (measures in cm).

7) PHOTON-STOP IMPEDANCE MEASUREMENT

The impedance can be inferred from measurements of the transmission scattering parameters (S) of the device. This method was proposed in the 70's by M. Sands and J. Rees from SLAC [9] and then developed by Hahn and Pedersen[10], and Palumbo and Vaccaro[11,12] . The basic idea is that relativistic beam fields in the vacuum chamber can be simulated by means of TEM waves propagating exited in a wire. Suggesting a very small wire radius, the impedance $Z(w)$ can be estimated with the simple formula:

$$Z(\boldsymbol{w}) = 2R_0 \left(\frac{S_{21} - S_{21}^{REF}}{S_{21}^{REF}} \right)$$
(1)

where $R_0 = (Z_0/2\pi) \cdot \ln(b/a)$- is the characteristic impedance of coaxial line with a and b as the radii of the inner and outer conductors, S_{21} is the transmission parameter of the

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component under test (photon-stop), S_{21}^{REF} - the parameter of the unperturbed coaxial line of the same length.

When the central wire has small but finite radius a more accurate formula[4]can be used for the estimation of the impedance, which approaches to the Sands and Rees formula (1), when the wire radius tends to zero. For the measurement we propose to use a pipe with the photon stop inside. The wire should not be thicker than 50-100 microns. Special matching cones on both ends of the wire allow to match the impedance of the pipe coaxial line with the 50 Ω impedance of the cables from the network analyzer. As a reference, the same line is used with the photon-stop pulled back.

In this case the impedance contribution of the matching cones, signal attenuation in the cables and the pipe itself will be subtracted. To avoid a large sagitta (hanging through by gravity) of the wire the pipe should be installed vertically. The coupling impedance can in a further step be measured with the structure installed in an accelerator. A number of methods can be used to measure the longitudinal and transverse impedances by measuring the appropriate beam parameters. The main difficulty is the fact that there are a large number of other components, which also influence these parameters. So, for such measurements a high sensitivity of the diagnostics equipment is required. The possibility to measure the photon-stop impedance on the beam is under study.

8) SHORT- AND MID-TERM PHOTON-STOP R&D – TASK LIST

The short (months) and mid-term (1-2 years) tasks in the R&D path toward a VLHC photon-stop is presented in Table 4. The full blown vacuum tests, as described in part 6 are not listed here for obvious reasons.

TASK	DESCRIPTION
Engineering design - continued	refining engineering design of the VLHC photon-stop
Impedance Simulations - continued	continued numerical calculations of the photon-stop impedance
Vacuum Simulations	numerical simulations of the vacuum conditions in a VLHC-2 beam-tube with a photon-stop
Stage 1 Test	thermal test of photon-stop prototype including fabrication of prototype
Stage 2 Test	impedance Test with "wire-method"
Stage 3 Test	cryogenic test of photon-stop at Fermilab

Table 4: Short- and mid-term task-list for Photon-Stop Vacuum Measurements.

References:

[1] I. Terechkine, "*Synchrotron Radiation in the VLHC*", Fermilab, Technical Division Note, unpublished, 01/01.

[2] P. Bauer et al., "*A Photon-Stop for VLHC-2 – Engineering Design – Part I*", Fermilab, Technical Division Note TD-01-023, 04/01.

[3]   N. Solyak et al., "*A Photon-Stop for VLHC-2 – Impedance Calculations*", Fermilab, Technical Division Note TD-01-014, 04/01.

[4]   S. Sharma et al., "*High Heat Load Absorbers for the APS Storage Ring*", Proceedings of the 1st International Workshop on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation, July 2000, PSI, Wurenlingen, Switzerland.

[5]   P. Bauer et al., "*A Photon-Stop for VLHC-2 – Engineering Design – Part 2*", Fermilab, Technical Division Note, in preparation.

[6]   V. Anashin et al., "*Synchrotron Radiation Induced Gas Desorption from a Prototype LHC Beam Screen at Cryogenic Temperature*", Cern, LHC Project Note 7, Sept. 1995.

[7]   W.C. Turner, "*Beam Tube Vacuum in Future Superconducting Proton Colliders*", SSCL Preprint 564, Oct. 1994.

[8]   P. Limon et al., "VLHC-Feasibility Study", Fermilab, TM-2149, May 2001.

[9]   M.Sands, J.Rees, SLAC-Report PEP-95, (1974).

[10] H.Halm, F.Pedersen, BNL 50870, Particle Acc and HV Machines TID-4500, (1978).

[11] L.Palumbo, V.Vaccaro, LFN-89/035(P), (1989).

[12] A.Argan, L.Palumbo, M.Masullo, V.Vaccaro, "On the Sands and Rees Measurement Method of the Longitudinal Coupling Impedance", Proc. of the PAC'99, p.1599, (1999).